Autonomous Guidance & Control

New Millennium Theme Presentation

Sima S. Lisman

Automation and Control Section (345)

June 24, 1996

Jet Propulsion Laboratory

California Institute of Technology

Pasadena, Ca 91109

Autonomous Guidance & Control
NMP Theme Presentation
Agenda

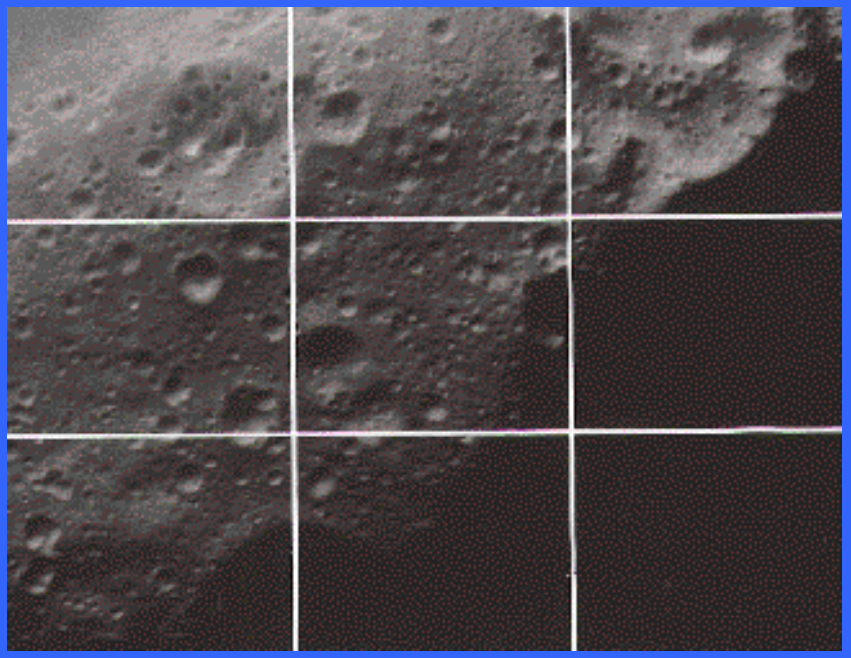
- Acknowledgments
- Overall Vision
- Autonomous Guidance and Control (G&C) Vision
- Autonomy 5-Year Roadmap
- Key G&C Technologies
- Autonomous G&C Roadmap
- Technology Implementation for DS-1
- G&C Technology Comparison
- DS-1 Spacecraft Drawing and H/W Arrangement
- Representative DS-1 S/C Characteristics
- Overview of Autonomous G&C for DS-1
- Status of Autonomous G&C for DS-1
- DS-1 Spacecraft Flight Software Architecture
- DS-1 Autonomous G&C Architecture
- DS-1 Autonomous G&C State Diagram
- G&C Development Process
- Summary

Autonomous Guidance & Control
NMP Theme Presentation
Acknowledgments

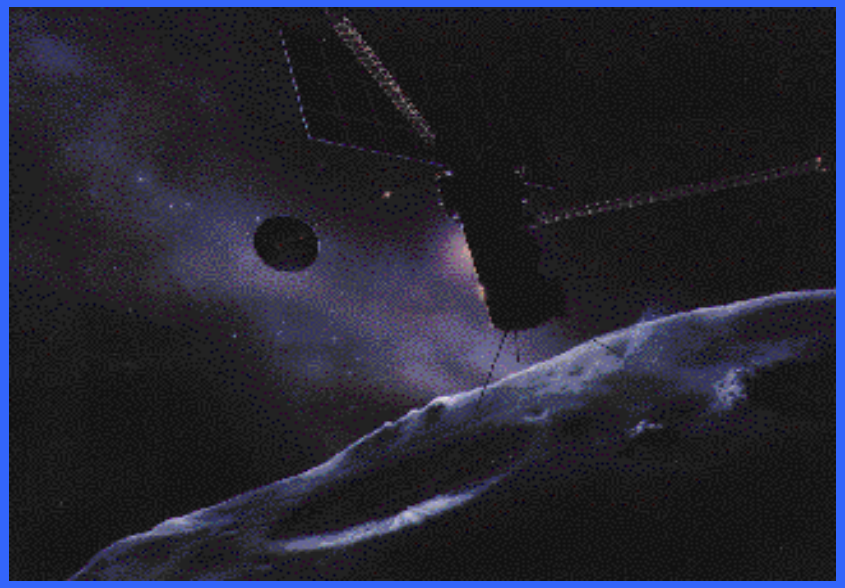
- A. Aljabri (345)
- S. Bhaskaran (312)
- W. Breckenridge (345)
- J. Cameron (345)
- D. Chang (345)
- C. Chu (345)
- J. Cloots (Microcosm)
- K. Gostelow (345)
- F. Hadaegh (345)
- S. Joshi (345)
- B. Lurie (345)
- E. Mettler (345)
- G. Man (345)
- E. Riedel (312)
- G. Singh (345)
- S. Sirlin (345)
- B. Smith (395)
- L. Wood (312)

AUTONOMOUS GUIDANCE, NAVIGATION & CONTROL

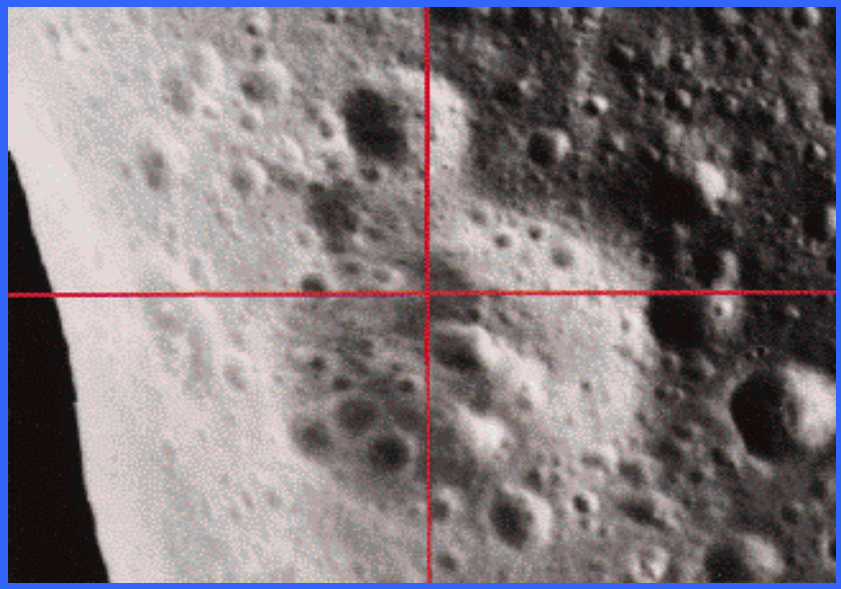
AUTONOMOUS MANEUVER & NAVIGATION



AUTONOMOUS FEATURE RECOGNITION



AUTONOMOUS LANDING



AUTONOMOUS TARGET REFERENCED POINTING

Autonomous Guidance & Control
NMP Theme Presentation
Autonomous Guidance and Control Vision

- **High-Level Commanding and Autonomous Execution**
  - On-Board Precision Pointing
  - On-Board Turn Planning and Execution
  - On-Board Constraint Checking during Turn Planning and Execution
  - On-Board Maneuver Execution

- **Autonomous Feature Recognition**
  - On-Board Extended Body Centroid ID
  - On-Board Shape/Spin Characterization
  - On-Board Topography Mapping
  - On-Board Feature/Target Recognition

Mission Operations Savings

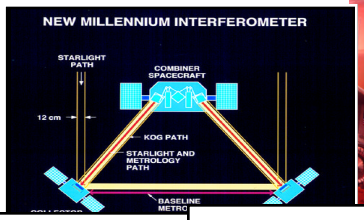
Enabling Future Exploration

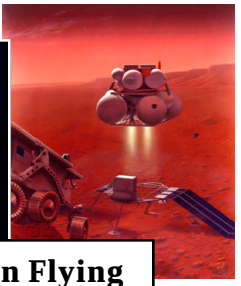
- **Autonomous Landing**
  - On-Board Drag/Atmosphere/Gravity Modeling
  - On-Board Hazard Avoidance Planning
  - On-Board Terminal Guidance and Descent
  - On-Board Precision Landing

- **Autonomous-Target Referenced Pointing**
  - On-Board Image-Based Pointing
  - On-Board Feature/Target tracking
  - On-Board Precision Pointing

More Science

Autonomy 5-Year Roadmap





	CY96	CY97	CY98	CY99	CY00
	Enables affordable new exploration				
Target Technology Experiment Mission				Flyby (Poorly-known targets asteroids & comets)	Formation Flying (Multi-platform missions) → Vision
Planning/ Scheduling & Fault Protection	Self-Directing Self-Protecting	• Priority-based planning • Model-based fault diagnosis	• Replanning & time-limited planning • Model-based recovery		Multi-Spacecraft • Contingency planning • Active diagnostic testing
Modular & Scaleable Architecture		• Partial modular flight s/w architecture • 10% reuse s/w	• Modular flight s/w architecture • 30% reuse s/w		• Modular flight/ground s/w architecture • 70% reuse s/w
Navigation		Autonomous deep space optical navigation for cruise		Autonomous deep space formation navigation	Autonomous navigation for rendezvous & landing
Guidance & Control	Self-Mobilizing	Onboard attitude planning & control for autonomous SEP cruise & flyby		Two spacecraft formation keeping	Multi-Platfrom onboard initialization & formation keeping
Onboard Science	Self-Recognizing			Feature recognition & retargeting	Adaptive object recognition
Justified Operations	PI-Directing	Beacon operations with limited data analysis & summary		Semi automated mission planning	PI controlled mission planning

Courtesy of G. Man

Autonomous Guidance & Control
NMP Theme Presentation
Key G&C Technologies

AUTONOMOUS FUNCTIONS

- **Estimation**
  - Attitude Determination
  - Target Reference Tracking
  - Calibration of Actuators/ Sensors
  - Guidance Functions
- **Control**
  - Attitude Control
  - Precision Pointing & Tracking
  - Flexible Body Control
  - Disturbance Management
- **On-Board Planning/Execution**
  - G&C Activity Planning, Replanning, and Execution
  - G&C H/W Fault Diagnostics
  - Momentum Management
  - Control Loop Reconfiguration

ENABLING TECHNOLOGIES

- **Autonomous ACS Architecture**
  - Artificial Intelligence
  - Knowledge Representation
  - Fuzzy-Neural Nets
  - Supervisory Control
  - Expert Systems
  - Micro-ACS Instrumentation
- **ACS Reconfigurable Control**
  - Performance/Robustness Tuning
  - Intelligent Control
  - Adaptive/Robust Control
  - Fault Detection, Localization & Recovery
- **On-Board Learning**
  - Parameter Estimation
  - Nonlinear Estimation
  - Disturbance Identification
  - Multiple Hypothesis Testing
  - Control-Disturbance Interaction
- **Advanced Tools and Processes**
  - Rapid Prototyping Tools for End-End Real-Time Analysis and Simulation
  - Integrated Tools for Design and Testing of Highly Autonomous S/C
  - Common Flight Software
  - Highly Modular Plug & Play Tools and Application

Autonomous Guidance & Control
NMP Theme Presentation
Autonomous G&C Roadmap

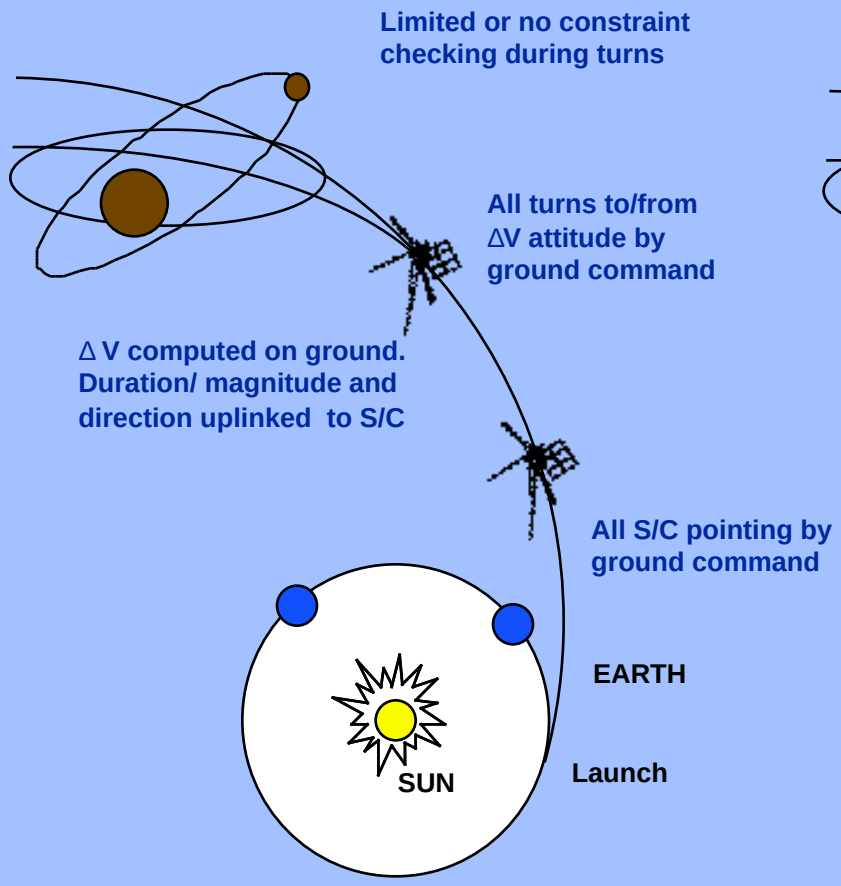
Technology	CY 1997	CY 2000	Vision
Ion Propulsion System (IPS) Thrust Vector Control	-Analysis & Software including autonomous execution		
Precision Attitude Determination & Control	-Autonomous attitude pointing & stabilization w/flexible solar arrays and IPS -Integration with autonomous Navigation software	-Precision attitude determination & control SW refined -Multi-platform attitude determination & control S/W -System ID of modal dynamics	S/W for: -Multi-vehicle synchronization -Formation Flying -Laser Metrology -Full 6-DOF attitude control
Target/Reference Tracking	-Onboard feature tracking S/W -Extended body center finding analysis & S/W	-Previous capabilities adapted to orbital operations	-Auto flyby sequencing S/W
On-Board Learning & Reconfigurable Control	-Onboard parameter estimation S/W -Performance robustness tuning S/W	S/W for: -Active momentum management -Onboard disturbance ID -Shape/spin characterization -Drag/atmospheric modeling -Gravity mapping &Topography -Reconfigurable control S/W	S/W for: -Momentum management for active comets -Non linear estimation -Multiple hypothesis testing -Control disturbance interaction -Intelligent Control S/W
Advanced Tools & Process Improvements	-Rapid prototyping tools for end-end real-time analysis & simulation -Common, autonomous FSW architecture -Streamlined H/W in the loop testing	-Integrated tools for design and testing of highly autonomous S/C -Common Flight software elements	-Highly modular, plug & play tools and applications

Autonomous Guidance & Control
NMP Theme Presentation
Technology Implementation for DS-1

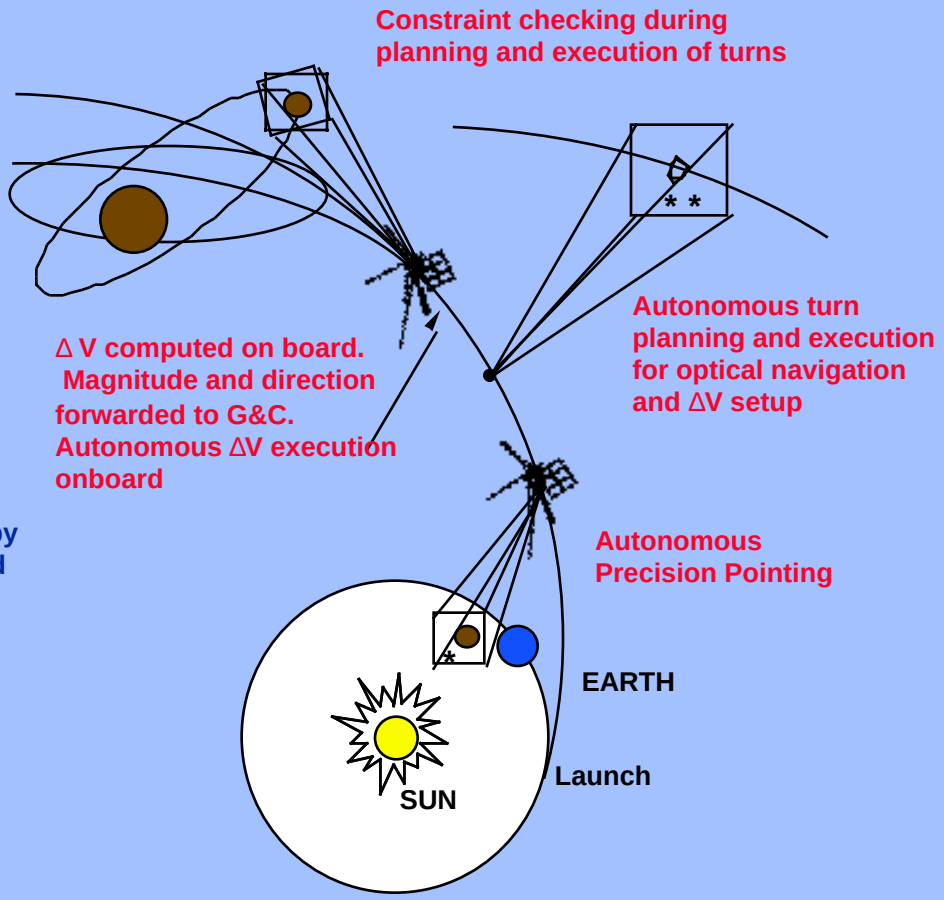
- DS-1 autonomous technologies are to be implemented during calendar years '96-97
- Significant strides made by incorporation of Autonomous Remote Agent and Optical Navigation
  - Autonomous Remote Agent provides high-level planning and execution
  - Autonomous Optical Navigation provides on-board S/C trajectory, ephemeris and desired delta-V information
- Autonomous G&C capabilities selected to support and enhance the above
- Emphasis is placed on High-Level Commanding and Autonomous Execution & Advanced Tools and Process Improvements within the G&C area

Autonomous Guidance & Control
NMP Theme Presentation
G&C Technology Comparison

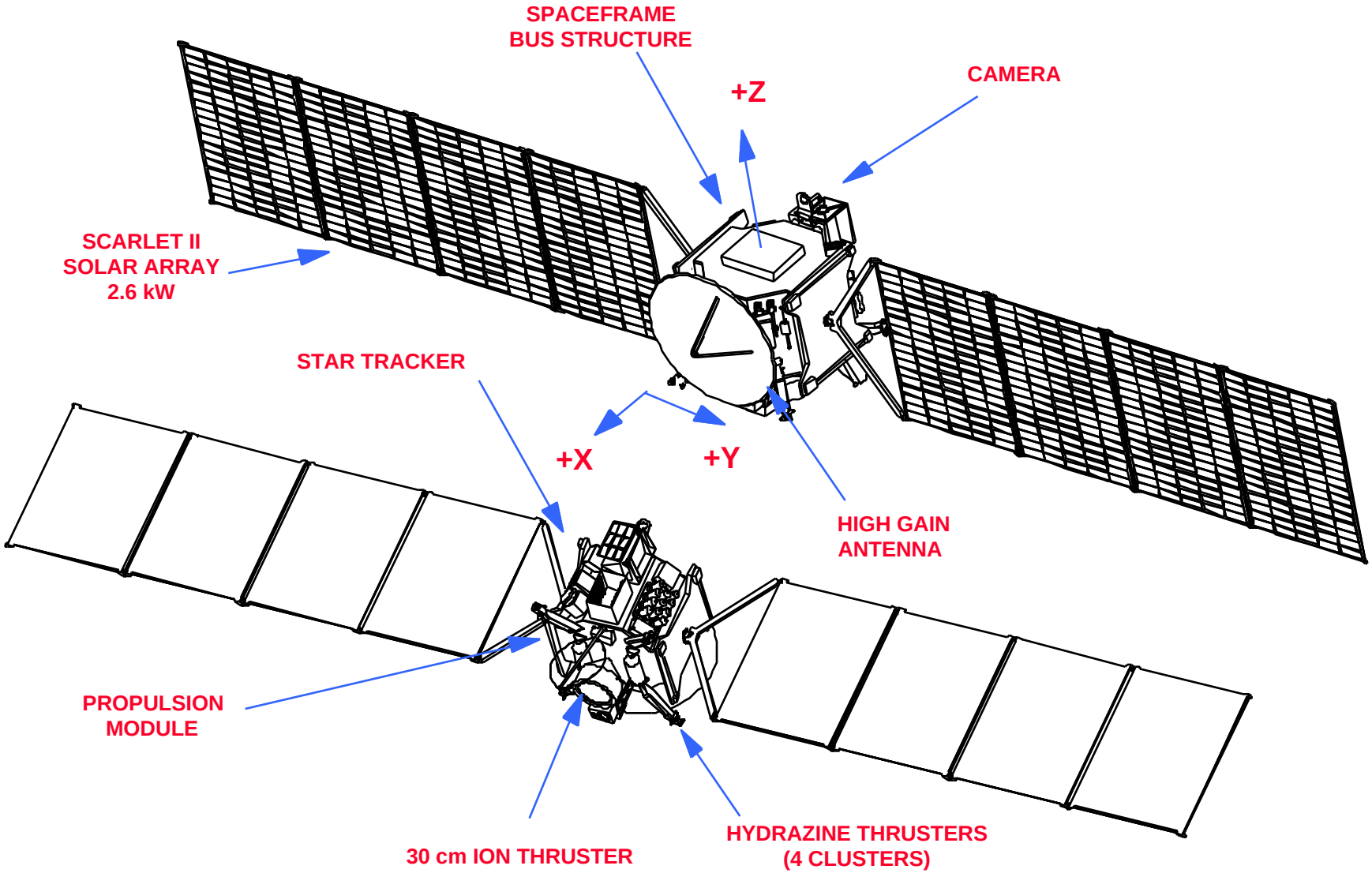
CONVENTIONAL APPROACH



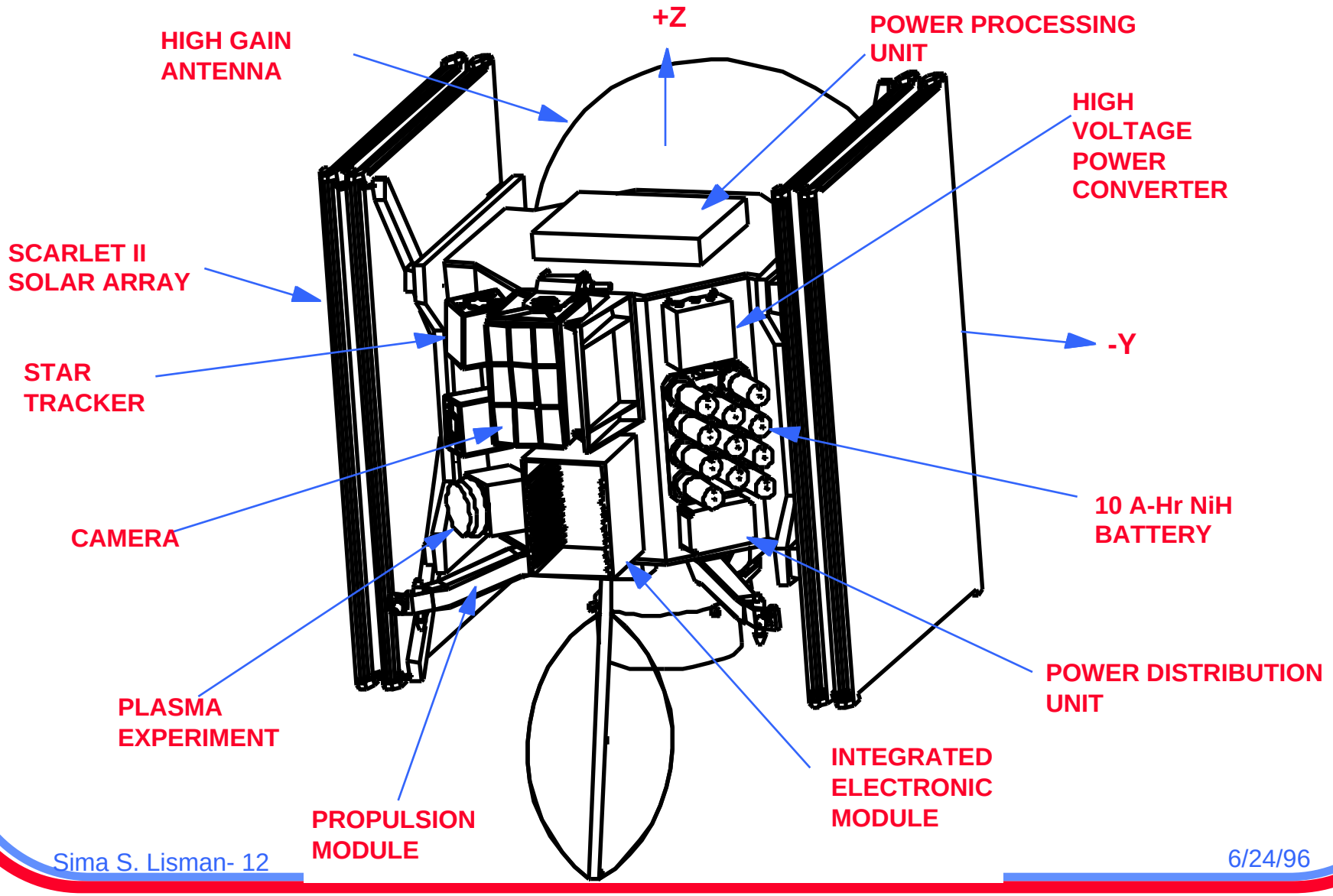
AUTONOMOUS APPROACH



Autonomous Guidance & Control
NMP Theme Presentation
DS-1 Spacecraft Drawing



Autonomous Guidance & Control
NMP Theme Presentation
DS-1 H/W Arrangement



Representative DS-1 S/C Characteristics

- S/C launch mass of approx. 430 kg
- S/C moments of inertia (Deployed, Beginning of mission)
  - I_{xx} = 910 kgm^2, I_{yy} = 68 kgm^2, I_{zz} = 908 kgm^2
- Solar panel system modes of (2% damping):
  - 0.28 Hz (1st symmetric bending O/P)
  - 0.71 Hz (1st anti-symmetric bending O/P)
  - 1.7 Hz (2nd symmetric bending O/P)
  - 2.1 Hz (1st symmetric bending I/P), ...
  - 5 Hz (1st symmetric torsion)
- Stellar Reference Unit overall accuracy of 675 μrad (in X&Y), noise equivalent angle of 75 μrad, and bias of 450 μrad (all 3 σ), autonomous all-sky initialization and track
- Rate Sensor angle random walk of 9μrad/root second (3 σ), at 1 Hz update
- RCS thrust level of 0.5-0.25 N (blow down), minimum impulse bit range of 13-8 mNs, Cassini type misalignments, moment arms of 0.63-0.43 m
- Ion engine thrust of 20-90 mN, thrust stability of 2%, thrust vector misalignment of 17.5 mrad; long term alignment stability of 6.4 mrad (all 3 σ)
- Solar Panel harmonic drive actuators with overall accuracy of ± 0.7 mrad (3 σ), step size of ± 0.35 mrad
- Ion engine actuator : TBD

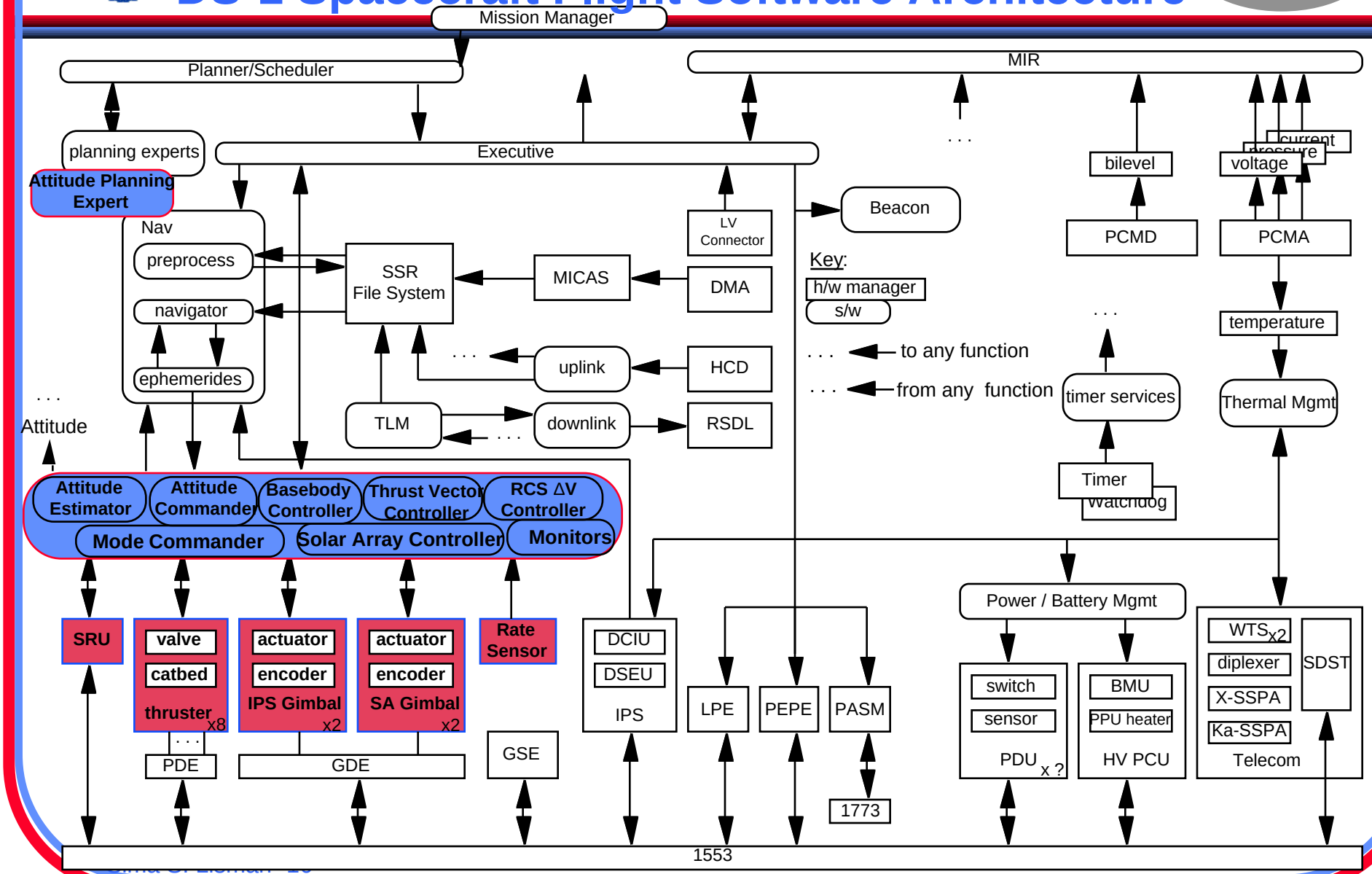
Overview of Autonomous G&C for DS-1

- The Autonomous G&C for DS-1 provides the following :
  - Attitude determination using star tracker and rate sensor
  - Turn planning : Turn time computation and geometric/dynamic constraint checking
  - Turn expansion : Low-level turn commands from high-level specifications
  - Turn execution with
    - Special accommodation of panel gimbal degree of freedom to maintain sun-point during turns
    - Constraint checking (geometric/dynamic) during turns
  - Inertial and body vector maintenance and update
  - Attitude control (inertial hold and turns) using hydrazine thrusters
  - Thrust vector control of the ion engine gimbal
  - Reaction Control System (RCS) delta-V execution
  - Pointing control of the solar panel gimbals
  - S/C behavior monitoring/diagnostic data for fault detection and isolation
  - Telemetry for the ground

Status of Autonomous G&C for DS-1

- Provided joint demonstration of autonomous G&C and Autonomous Navigation technologies for a prototype NM mission in September ‘95
- DS-1 Flight Team formed December ‘95
- Developed architecture for Autonomous G&C for DS-1
- Began rapid prototyping style code development in February ‘96
- Delivered first version of operational G&C code for DS-1 in March ‘96
- Plan to deliver full functionality G&C code by February ‘97 and ATLO ready code by July ‘97

Autonomous Guidance & Control
NMP Theme Presentation
DS-1 Spacecraft Flight Software Architecture



Autonomous Guidance & Control
NMP Theme Presentation
DS-1 Autonomous G&C Architecture

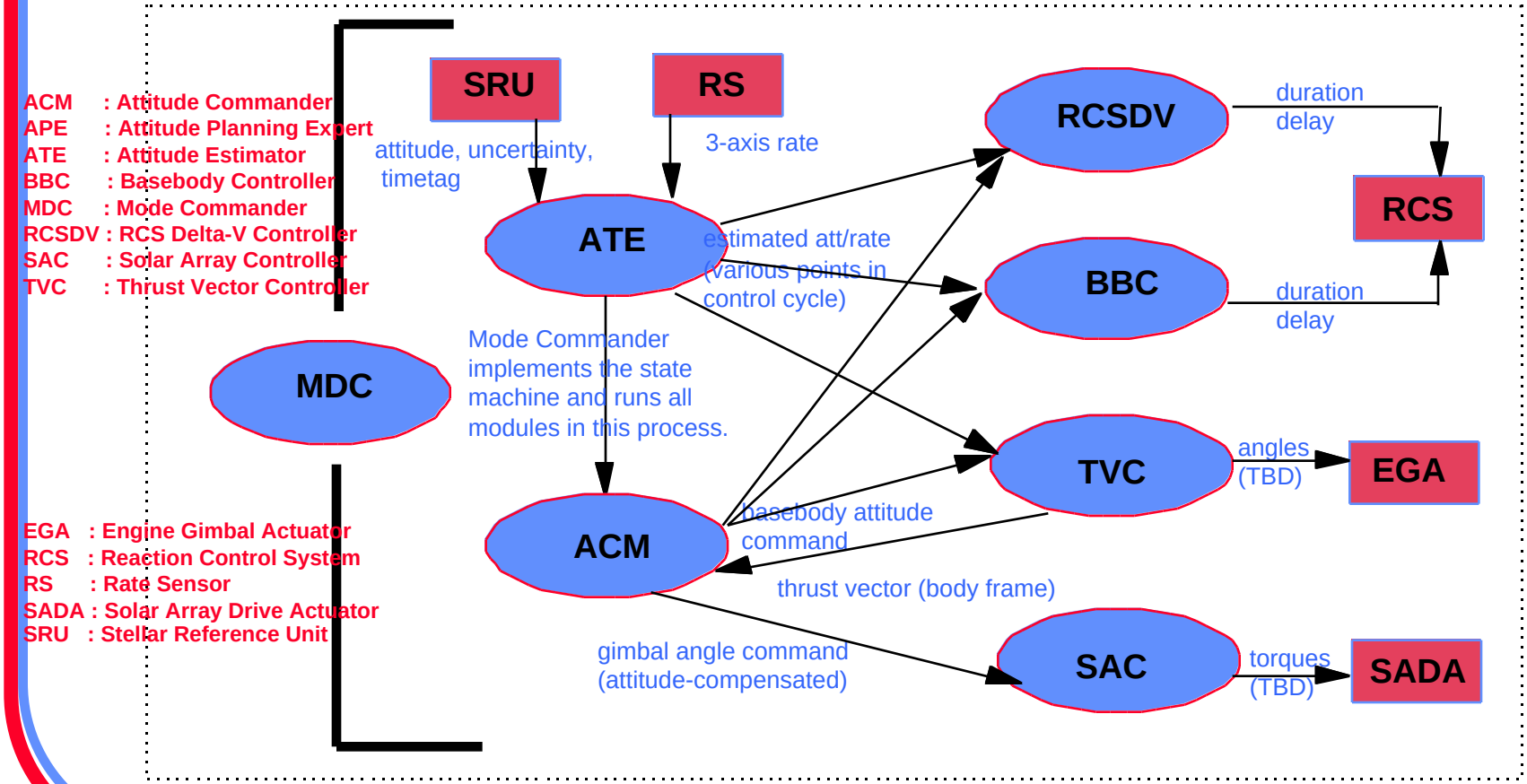
APE

- ACS consists of 2 VxWorks processes. APE process does not require real-time priority
- All communications outside processes implemented via IPC messages, not shown here
- All ACS H/W Managers communicate with Bus Manager, via IPC

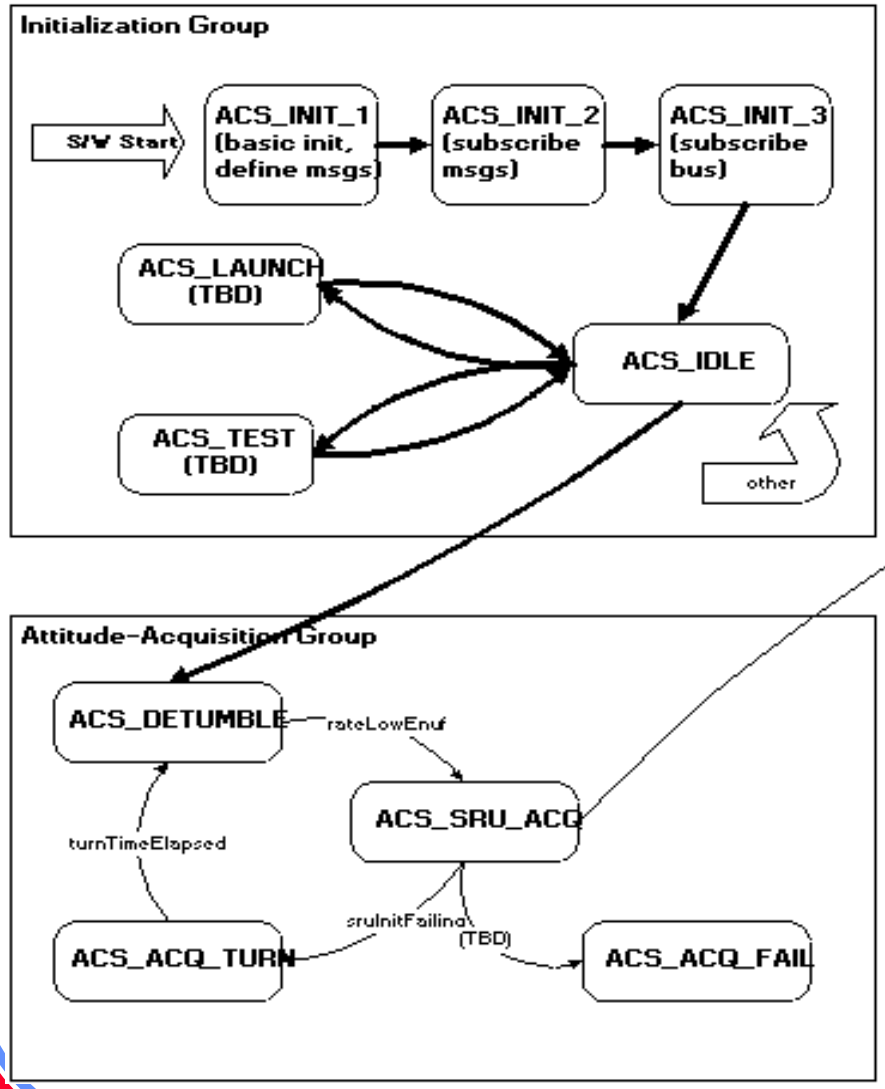
ACS H/W Manager

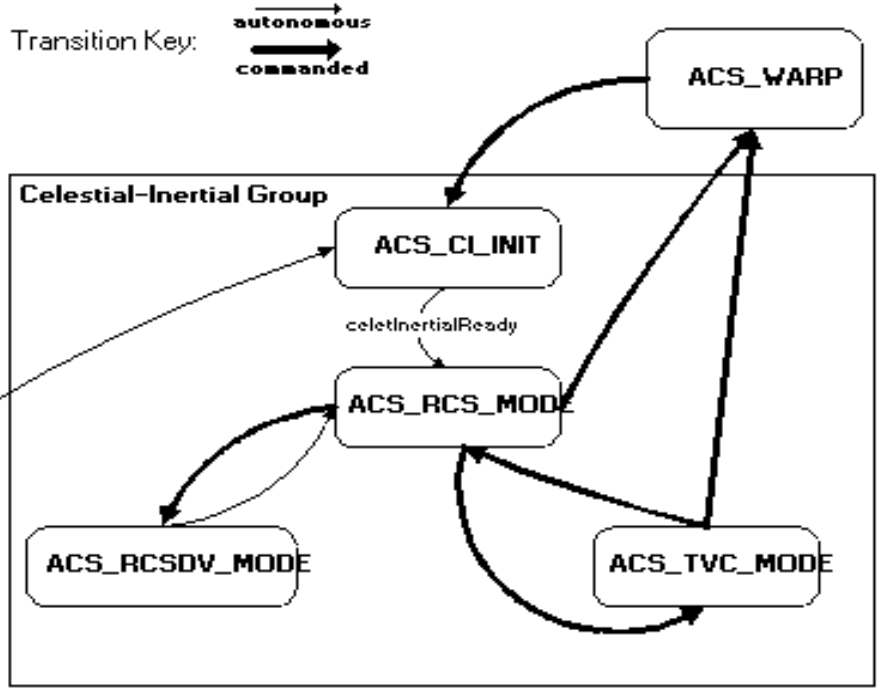
ACS S/W Module

VxWorks Process



Autonomous Guidance & Control
NMP Theme Presentation
DS-1 Autonomous G&C State Diagram

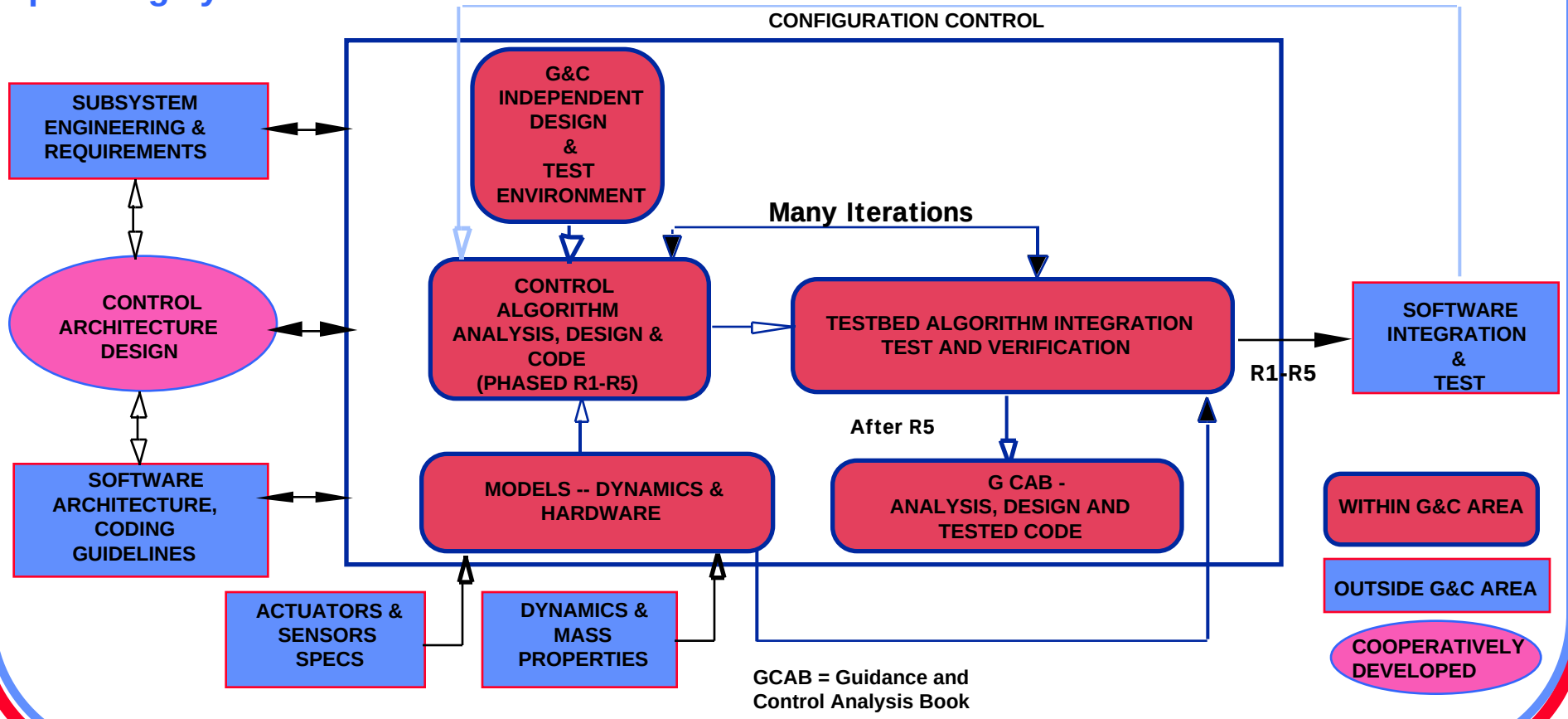




- Many G&C state changes are autonomous
- Those changes requiring coordination with higher level modules are commanded
- G&C can autonomously place the S/C in a safe state following faults

Autonomous Guidance & Control
NMP Theme Presentation
G&C Software Development Process

- Rapid development of the G&C software, utilizing "C" language and modern real-time Operating System (VxWorks)
- Spiral development model, using multiple deliveries, each with increasing functionality
- Iterative design and testing using common testbed environment, running under multiple operating systems



Summary

- Well in process of providing autonomous G&C capabilities for NM DS-1
- Have a solid autonomous G&C technology roadmap with long term vision
- Proceeding with autonomous G&C technology development in preparation for future New Millennium missions
  - Orbital operations for deep space and Earth orbiting missions
  - Formation Flying
  - Smart small body landing
- Autonomous G&C area is bringing exciting and enabling capabilities to the New Millennium Program and future NASA missions